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The optical counterpart of the bright X-ray transient Swift J1745-26

T. Muñoz-Darias[1], A. de Ugarte Postigo[2,3], D. M. Russell[4,5], S. Guziy[6,2], J. Gorosabel[2,7,8], J. Casares[4,5], M. Armas Padilla[9], P. A. Charles[1,10], R. P. Fender[1], T. M. Belloni[11], F. Lewis[12], S. Motta[13], A. Castro-Tirado[2], C. G. Mundell[14], R. Sánchez-Ramírez[2], C. C. Thöne[2]

[1]*School of Physics and Astronomy University of Southampton, Southampton, Hampshire, SO17 1BJ, United Kingdom*
[2] *Instituto de Astrofísica de Andalucía (IAA-CSIC), Glorieta de la Astronomía s/n, 18008, Granada, Spain.*
[3]*Dark Cosmology Centre, Niels Bohr Institute, Juliane Maries Vej 30, Copenhage Ø, 2100, Denmark*
[4]*Instituto de Astrofísica de Canarias (IAC), Vía Láctea s/n, La Laguna, E-38205, S/C de Tenerife, Spain*
[5]*Departamento de Astrofísica, Universidad de La Laguna, La Laguna, E-38205, S/C de Tenerife, Spain*
[6] *Nikolaev National University, Nikolska 24, Nikolaev, 54030, Ukraine*
[7] *Unidad Asociada Grupo Ciencia Planetarias UPV/EHU-IAA/CSIC, Departamento de Física Aplicada I, E.T.S. Ingeniería, Universidad del País Vasco UPV/EHU, Alameda de Urquijo s/n, E-48013, Bilbao, Spain.*
[8] *Ikerbasque, Basque Foundation for Science, Alameda de Urquijo 36-5, E-48008 Bilbao, Spain.*
[9] *Astronomical Institute 'Anton Pannekoek', University of Amsterdam, Science Park 904, 1098 XH, Amsterdam, the Netherlands*
[10]*Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, Republic of South Africa*
[11] *INAF-Osservatorio Astronomico di Brera, Via E. Bianchi 46, I-23807 Merate (LC), Italy*
[12]*Faulkes Telescope Project, University of Glamorgan, Pontypridd, CF37 1DL, UK*
[13] *European Space Astronomy Centre (ESAC)/ESA, PO Box 78, E-28691 Villanueva de la Cañada, Madrid, Spain*
[14] *Astrophysics Research Institute, Liverpool John Moores University, Twelve Quays House, Egerton Wharf, Birkenhead, CH41 1LD, UK*

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ABSTRACT

We present a 30-day monitoring campaign of the optical counterpart of the bright X-ray transient Swift J1745-26, starting only 19 minutes after the discovery of the source. We observe the system peaking at $i' \sim 17.6$ on day 6 (MJD 56192) to then decay at a rate of ~ 0.04 mag day^{-1}. We show that the optical peak occurs at least 3 days later than the hard X-ray (15-50 keV) flux peak. Our measurements result in an outburst amplitude greater than 4.3 magnitudes, which favours an orbital period $\lesssim$ 21 h and a companion star with a spectral type later than $\sim$ A0. Spectroscopic observations taken with the GTC-10.4 m telescope reveal a broad (*FWHM* $\sim 1100 \ \mathrm{km\,s^{-1}}$), double-peaked Hα emission line from which we constrain the radial velocity semi-amplitude of the donor to be $K_2 > 250 \ \mathrm{km\,s^{-1}}$. The breadth of the line and the observed optical and X-ray fluxes suggest that Swift J1745-26 is a new black hole candidate located closer than $\sim$ 7 kpc.

Key words: accretion, accretion discs, X-rays: binaries, indivudual:Swift J1745-26.

1 INTRODUCTION

Low mass X-ray binaries (LMXBs) are interacting binaries harbouring a neutron star (NS) or a black hole (BH) accreting from a companion star typically lighter than the Sun. Accretion takes place via an accretion disc, where gravitational energy is efficiently converted into radiation (Shakura & Sunyaev 1973). LMXBs are multiwavelength sources, emitting from high-energies to radio through different thermal and non-thermal processes (e.g. Remillard & McClintock 2006, Fender 2006). If the mass transfer rate is high enough, these systems are always bright, with X-ray luminosities in the range $L_{\rm X} \sim 10^{36-39}$ erg s^{-1}. They are so-called persistent sources, whereas LMXBs with lower mass transfer rates tend to be found as X-ray binary transients (XRTs). These objects spend most part of their lives in a dim, quiescent state, displaying luminosities as low as $L_{\rm X} \sim 10^{31}$ erg s^{-1}. However, with recurrence times of a few months to decades, they undergo periods of activity, becoming as bright as persistent systems. It is during these outbursts, typically lasting a few weeks to months, when they are discovered by X-ray telescopes and subsequently studied using multiwavelength facilities.

Active X-ray binaries display a well known phenomenology at high energies (e.g. van der Klis 2006; Belloni et al. 2011). They also show very distinctive optical features, such as broad double-peaked emission lines testifying to the presence of an accretion disc (e.g. Charles & Coe 2006). Galactic BHs are mostly found as XRTs, whereas the vast majority of the persistent population harbour NSs. This is not well understood yet but could be related to the dependence on the compact object mass of the critical mass transfer rate for a system to be persistent (e.g. King et al. 1996).

Swift J1745-26 (Swift J174510.8-262411; hereby J1745) was discovered by the Burst Alert Telescope (BAT; Barthelmy et al.

Table 1. Observing log.

MJD	Telescope	Band(s)	T$_{exp}$ (s)
56186.406	FTS	*V*, *R*, i'	200, 100, 100
56187.85	GTC	i'	60 ($\times$ 10)
56187.87	GTC	Spec. R1000R	900 ($\times$ 2)
56187.89	GTC	Spec. R1000B	900 ($\times$ 2)
56188.88	IAC80	I	300 ($\times$ 8)
56191.418	FTS	*V*, *R*, i'	200, 100, 100
56191.817	IAC80	I	30 ($\times$ 11)
56195.422	FTS	*V*, i', *R*	200, 100, 100
56195.829	LT	i'	100
56198.825	LT	i'	100
56199.823	LT	i'	100
56201.827	LT	i'	100
56204.46	FTS	*R*, i'	100 ($\times$ 2), 100
56204.877	CAHA-2.2m	u', g', r', z'	4$\times$(100, 100, 100, 100)
56206.819	LT	i'	100
56207.819	LT	i'	100
56208.818	LT	i'	100
56209.817	LT	i'	100
56210.817	LT	i'	100
56211.816	LT	i'	100
56214.811	LT	i'	100
56215.812	LT	i'	100

2005) on board the *Swift X-ray observatory* on September 16, 2012 (Cummings et al. 2012a, 2012b). Subsequent observations performed by *Swift* and *INTEGRAL* at X-ray wavelengths showed a significant flux increase during the following days together with X-ray properties resembling those typically seen in BH transients (e.g. Sbarufatti et al. 2012, Tomsick et al. 2012, Belloni et al. 2012). Multiwavelength observations supported the X-ray binary nature of the system, although a definitive evidence for a BH accretor has not been reported yet (see Rau et al. 2012, de Ugarte Postigo et al. 2012, Russell et al. 2012 for optical/infrared; see also Miller-Jones & Sivakoff 2012, Corbel et al. 2012 for radio).

Here, we present the first study of the optical counterpart of J1745. It includes spectroscopic data and multi-band photometric follow-up from a few minutes after its discovery until the source was no longer visible due to Sun constraints. We compare the outburst evolution in the optical, with that at high-energies (*Swift*/BAT 15-50 keV) and report the first constraints on some of the orbital parameters of the system.

2 OBSERVATIONS AND RESULTS

Our optical follow-up of J1745 began a mere 19 minutes after the *Swift*/BAT alert and continued for $\sim$ 30 days. Five different facilities were utilized: (i) the 2 m Faulkes Telescope South (FTS; located at Siding Spring, Australia), (ii) OSIRIS attached to the *Gran Telescopio de Canarias* (GTC) 10.4 m telescope in La Palma (Spain), (iii) the 2.0 m Liverpool Telescope (LT) also in La Palma, (iv) the IAC80 82 cm telescope in Tenerife (Spain) and (v) the 2.2 m telescope at Calar Alto observatory (CAHA-2.2m) in Almeria (Spain). An observing log is presented in Table 1. Observations were taken mostly using the Sloan i'filter, although *V* and *R* Johnson, I Bessel and Sloan u', g', r', z' bands were also used for some epochs. Bias and flat-field corrections were performed using IRAF routines and the flux of the optical counterpart was extracted and

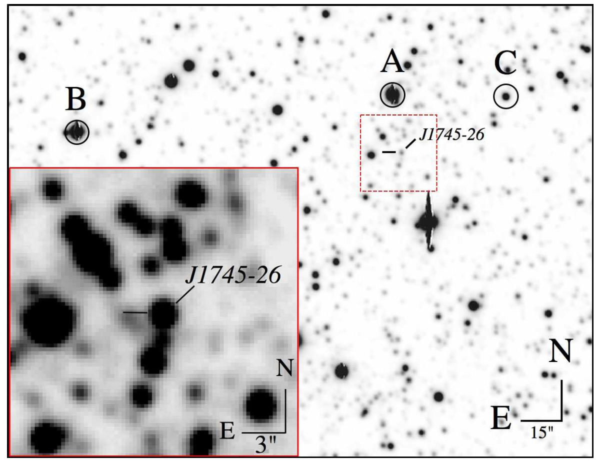

Figure 1. Finding chart of Swift J1745-26 in Sloan i' band taken with the GTC-10.4 m telescope. The refined object coordinates (J2000) are 17:45:10.85, -26:24:12.6, for which we estimate an absolute error of 0.3 $''$. The three comparison stars used to carry out the flux calibration are labelled as A (i'=13.4), B (i'=13.2) and C (i'=16.2).

calibrated using three photometric comparison stars (Fig. 1). The error in our absolute calibration is $\sim$ 0.1 mags. However, the relative errors between data points are much smaller, allowing us a detailed study of the outburst evolution. The i'band light-curve is presented in Fig. 2, for which, we also used I band data converted to i'using the transformations of Jordi et al. (2006). In total, our photometry covers the outburst evolution of J1745 with 19 visits.

The source is observed to brighten during the first $\sim$ 6 days after the X-ray discovery at an average rate of $\sim$ 0.1 mag day^{-1}, peaking at $i'\sim$ 17.6 between days 5–10. Since day 10, a decay down to $\sim$ 18.1 at a rate of $\sim$ 0.04 mag day^{-1} is observed. We note that given the quiescence level ($r'>$ 23.1) reported by Hynes et al. (2012), we missed the major part of the outburst rise. Observations with filters other than i'were also taken on a few occasions (Tab. 1). Our best *V* band determined magnitude is 20.0 ± 0.2 on MJD 56191, the other two epochs having larger errors and being consistent with the earlier one. On MJD 56204 using the CAHA-2.2m we measure g'=21.29 $\pm$ 0.12, r'=19.14 $\pm$ 0.04 and z'=16.82 $\pm$ 0.04, whereas the source was not detected in u'(>21). The same day we obtain i'=17.96 $\pm$ 0.03 and *R*=18.45 $\pm$ 0.04 using the FTS. We observe the *R*-i'colour to be 0.86 ± 0.09, 0.92 ± 0.08 and 0.97 ± 0.07 on days MJD 56186, 56191 and 56195, respectively. Then, after the peak flux (and transition towards softer states; Belloni et al. 2012), it becomes bluer, being 0.80 ± 0.05 on MJD 56204.

2.1 Spectroscopy

Four optical spectra were obtained on Sep 17, 2012 between 20:44:47 and 21:48:06 UT (i.e. only $\sim$ 35 hours after the discovery of the source) using the spectroscopic mode of OSIRIS/GTC. The system was at $i'\sim$ 18 magnitude at that time (see Fig. 2). Observations consisted of 2 $\times$ 900s exposures using the R1000R grating, which covers the range from 5000 to 10000 Å at a resolution power of $\lambda/\Delta\lambda \sim$ 1100, followed by 2 $\times$ 900s using the R1000B grating, with a wavelength coverage from 3600 to 7500 Å and a similar resolution. The slit was placed at the parallactic angle with a width of 1”. Unfortunately, observations were performed at a necessarily high airmass (> 2.0) and hence high extinction. This considerably limited our analysis, which was effectively restricted

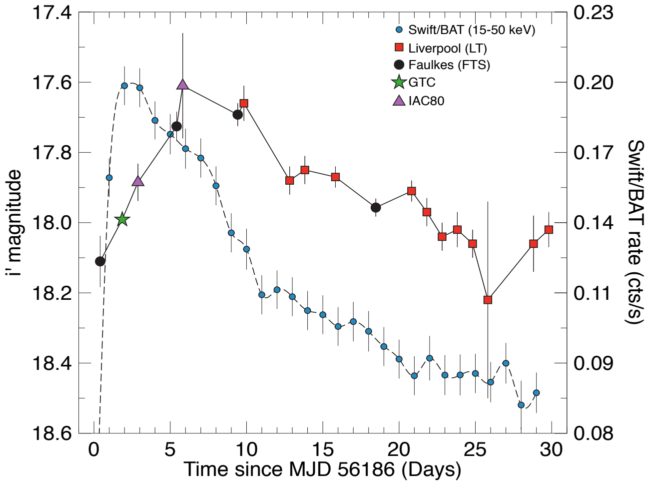

Figure 2. Optical i' light-curve of J1745 obtained by combining all the available photometry. The one-day average *Swift*/BAT (15-50 keV) lightcurve (rescaled and offset) is shown as a dashed line.

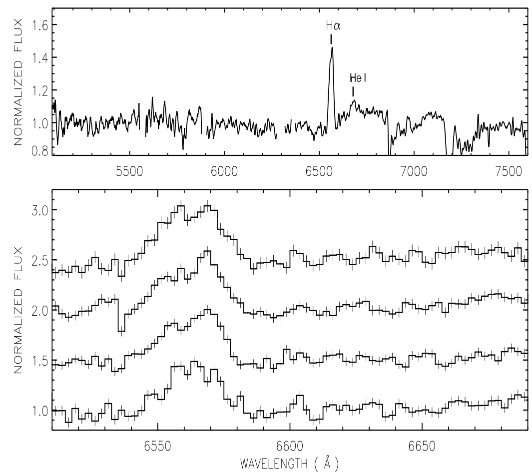

Figure 3. Top panel: normalized, average spectrum of J1745. Gaps are due to significant residuals after the sky subtraction. Bottom panel: zoom in of the Hα region. An offset of 0.5, 1. and 1.5 has been applied to spectra 2, 3 and 4, respectively.

to the 5000–7500 Å range covered in all the spectra. Data reduction was performed using standard IRAF procedures. No reliable flux calibration was possible due to the high airmass and variable conditions.

The spectrum is almost featureless in the 5000-7500 Å range (top panel in Fig. 3), except for the presence of a broad Hα emission line, which is clearly detected in the four individual spectra (see bottom panel in Fig. 3). This feature, typically observed in compact binaries, has a double-peaked, asymmetric profile, as expected from an accretion disc origin (Smak 1969). The shape of the line, in particular the blue peak, is seen to vary from spectrum to spectrum along the ~ 1 hour of our continuous monitoring (i.e. on time scales of ~ 15 min;). A Gaussian fit to the average Hα profile gives an equivalent width of $EW = 12.6 \pm 0.5$ Å and *FWHM*= 1115 ± 38 $\mathrm{km\,s^{-1}}$, whereas a peak-to-peak separation of 634 ± 18 $\mathrm{km\,s^{-1}}$ is obtained by fitting the line with two Gaussians. These measurements are consistent with those found in other X-ray binaries and are discussed in section 3. Finally, we note that the He I $\lambda 6678$ emission line, typically seeing in X-ray binaries, is also detected in the average spectrum of J1745 (top panel in Fig. 3).

3 DISCUSSION

We have studied the evolution of the optical counterpart of the X-ray transient Swift J1745-26 using photometry and spectroscopy. The spectrum is dominated by a broad (*FWHM* ~ 1100 $\mathrm{km\,s^{-1}}$), double-peaked Hα emission. Since these lines are known to be naturally formed in geometrically thin accretion discs (Smak 1969; Horne & Marsh 1986), the detection confirms both the association of the proposed optical counterpart with the X-ray source and its X-ray binary nature. Indeed, Hα is typically the most prominent optical emission line in X-ray binaries. Its *EW* can be as large as ~ 100 Å during the quiescence phase, becoming smaller ($\lesssim 20$ Å) during outburst. Therefore, our measurement ($EW \sim 13$ Å) is consistent with typical values observed during the earliest phases of the outburst (Fender et al. 2009).

Optical emission from active X-ray binaries arises in regions typically a few light seconds from the central object (see e.g. Hynes et al. 2006, Muñoz-Darias et al. 2007). This is mainly a result of X-ray reprocessing in the outer accretion disc (van Paradijs & McClintock 1994) but with some possible synchrotron jet contribution during hard X-ray states (Russell et al. 2006). Assuming that the Hα emission originates in a Keplerian, outer disc rim, the broadness of its profile tells us about the projected velocity of the regions closer to its inner radius (see Horne & Marsh 1986). Therefore, it is expected to, at least, depend on (i) the mass of the compact object, (ii) the orbital inclination and (iii) the size of the accretion disc. Not surprisingly, the systems with broadest Hα emission lines are found to be black holes with relatively high inclination e.g. XTE J1118+480 (*FWHM* $\sim$ 2500 $\mathrm{km\,s^{-1}}$; Torres et al. 2004). However, these measurements are taken in quiescence, where *FWHM* tends to be larger. For instance, in the BH binary GRS 1009-45 (Nova Vela 1993) *FWHM* $\sim$ 2000 $\mathrm{km\,s^{-1}}$ is measured during quiescence (Shahbaz et al. 1996; Filippenko et al. 1999) and *FWHM* ~ 1370 $\mathrm{km\,s^{-1}}$ in outburst (della Valle & Benetti 1993). NS systems seem to follow the same trend, but displaying lower velocities. In quiescence, Cen X-4 (low inclination; Shahbaz et al. 1993) shows *FWHM* $\sim$ 640 $\mathrm{km\,s^{-1}}$ (Torres et al. 2002) and XTE J2123-058 (grazing eclipses; Zurita et al. 2000) displays *FWHM* ~ 1300 $\mathrm{km\,s^{-1}}$ (Casares et al. 2002). For the latter, we estimate *FWHM* $\sim$ 500 – 600 $\mathrm{km\,s^{-1}}$ from the outburst spectrum shown in Hynes et al. (2001) and similar values have been observed in the eclipsing NS systems X1822-371 (Harlaftis et al. 1997) and EXO 0748-676 (Pearson et al. 2006) also during active phases. In light of the above, the *FWHM* measured for J1745 fits better with a BH scenario. However, we note that the amount of measurements available is relatively low and that other orbital parameters like the orbital period (i.e. size of the disc) should play a role in this discussion.

3.1 Outburst evolution

The photometric follow-up presented here started very promptly after the *Swift* alert. However, in our first measurement the system had already brightened considerably from its quiescent level (Hynes et al. 2012). During the first ~ 6 days, it kept rising at a rate of 0.1 mag $\mathrm{day^{-1}}$ before peaking at i'=17.6 . This rate seems

comparable with those seen in other XRTs. For instance, 0.36 mag day^{-1} was observed in XTE J1118+480 (Zurita et al. 2006), 0.14 mag day^{-1} in Aql X-1 (Shahbaz et al. 1998) and $\sim$ 0.25 mag day^{-1} in GRO J0422+32 (Castro-Tirado et al. 1997). After the peak, we see a decay at a rate of ~ 0.04 mag day^{-1} also comparable to the 0.05 – 0.07 mag day^{-1} rate reported in the aforementioned works. At the end of our 1-month monitoring J1745 was still bright and far from quiescence.

In Fig. 2 we compare the optical and (15–50 keV) X-ray lightcurves directly. This clearly shows the X-ray peak occurring $\sim$ 3d before the optical. X-rays peaking before the optical emission is at odds with some observations of other XRTs, where the flux is seen to peak (and/or suggested to rise) earlier in the optical (e.g. Orosz et al. 1997, Shahbaz et al. 1998, Zurita et al. 2006). This is traditionally interpreted as a proof of an *outside-in* outburst propagation. However, we note that those works typically use softer bands (e.g. 2–10 keV) than that here (15–50 keV). If we consider the canonical outburst evolution (e.g. Belloni et al. 2011), soft X-rays will peak several days later than the BAT data. Indeed, preliminary work on this source by part of our team shows that the maximum of the soft X-ray emission occurs around the same date or even later than the optical peak we report in this work [1].

Adopting the spectral parameters reported by Tomsick et al. (2012), the peak X-ray flux corresponds to 4.5$\times$10^{-8} ergs cm^{-2} s^{-1} in the 15–50 keV band (2.9$\times$10^{-8} ergs cm^{-2} s^{-1} within 2-10 keV). This corresponds to $\sim$ 1.2 Crab (2-10 keV), making J1745 one of the brightest XRTs in recent times. Assuming the accretion rate does not exceed the Eddington limit, the maximum distance to the source is $d \sim 7$ kpc for a BH and ~ 3 kpc for a NS[2]. After the BAT peak, J1745 is observed to move towards softer X-ray states (Belloni et al. 2012). Since BHs undergo state transition at luminosities higher than 2% of the Eddington luminosity (Maccarone 2003), we estimate $1 \lesssim \frac{d}{1\ \mathrm{kpc}} \lesssim 7$ for a BH accretor. Using these constraints on the distance, we have over plotted the X-ray flux reported by Sbarufatti et al. (2012) together with our optical measurement (MJD 56186; i.e hard X-ray state) in the optical–X-ray luminosity diagram presented by Russell et al. (2006; 2007) for $d = 1, 3$ and 7 kpc (Fig. 4). Here, we have used the the column density ($N_H = 1.70 \pm 0.04 \times 10^{22}$ cm^{-2}) from Tomsick et al. (2012). We find that regardless of the distance assumed, J1745 is consistent with being a BH in the hard state. However, we note that smaller N_H values will result in the system being consistent with a nearby ($\sim$ 1 kpc) NS LMXB.

3.2 Orbital parameters

The results presented here can be used to constrain the orbital parameters of J1745. The Hα peak-to-peak separation of 634 ± 18 $\mathrm{km\,s^{-1}}$ encodes information regarding the outer accretion disc velocity and was empirically related to the companion star projected velocity (K_2) by Orosz et al. (1994). Defining the outer disc velocity (v_d) as half of the peak-to-peak separation (i.e. $v_d = 317{\pm}9\ \mathrm{km\,s^{-1}}$ for J1745), they find that v_d/K_2 $\sim$1.1–1.25, which yields $K_2 > 250\ \mathrm{km\,s^{-1}}$ for J1745. We note that this value is a lower limit, since the Orosz et al. relation is obtained from quiescent accretion discs, which have larger v_d as result of a smaller

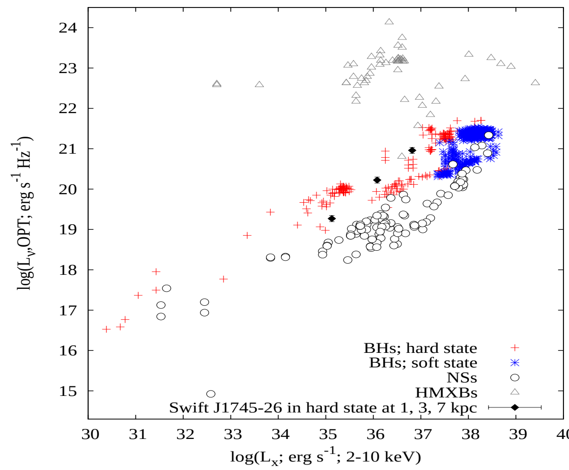

Figure 4. Optical/X-ray luminosity diagram from Russell et al. (2006; 2007). Black holes (soft and hard states), neutron stars LMXBs and high mass x-ray binaries (HMXBs) are included in the plot. Swift J1745-26 is consistent with being a BH in the hard state for the 3 distances considered (from left to right 1, 3 and 7 kpc; see text).

outer disc radius than in outburst (see Corral-Santana et al. 2013 for a discussion).

Our photometric data show a peak i' band magnitude of 17.6 corresponding to ~ 0.3 mJy. Assuming that the r'-$i' \cong 1.2$ colour (MJD 56204) is the same on MJD 56195 we obtain an outburst amplitude in the SDSS-r band $\Delta\, r' > 4.3$ from the quiescent level reported by Hynes et al. (2012). Shahbaz & Kuulkers (1998) found a relation between the outburst amplitude in V band (ΔV) and the orbital period (P_{orb}). Using $\Delta V = \Delta r'$we obtain $P_{orb} \lesssim 21$ hours. The last assumption seems reasonable since during the outburst the optical spectrum (once corrected from extinction) is expected to be disc dominated and relatively flat (van Paradijs & McClintock 1994) whereas a strong contribution from a redder companion star is expected in quiescence. We note that in the case of $\Delta V > \Delta r'$ the orbital period would be smaller. The Shahbaz & Kuulkers relation is valid for orbital periods $P_{orb} \lesssim 1$ day, which seems consistent with the dim, quiescent optical counterpart. Periods longer than $\sim$ 1d would imply evolved companion stars with likely brighter quiescence levels (see e.g. King 1993, Muñoz-Darias et al. 2008). Using the relation reported in Faulkner et al. (1972), our constraint on the orbital period results in a mean density for the donor star > 0.2 g cm^{-3}. For a main sequence companion, this limit yields a spectral type later than $\sim$ A0 (Cox 2000).

4 CONCLUSIONS

We have undertaken a detailed follow-up of the optical counterpart of the bright X-ray transient Swift J1745-26. All the observables suggest that Swift J1745-26 is a new black hole candidate, as proposed by preliminary analysis of X-ray observations. We provide the first constraint on some of the fundamental parameters of this X-ray binary.

- The optical spectrum of J1745 shows a strong, double-peaked Hα emission line from which we infer a donor radial velocity semi-amplitude of $K_2 > 250\ \mathrm{km\,s^{-1}}$. We also show that the breadth of this line (*FWHM* $\sim 1100\ \mathrm{km\,s^{-1}}$) suggests a black hole accretor.

[1] See http://www.rssd.esa.int/SD/INTEGRAL/images/POM2/2013-01.jpg
[2] Here we extrapolate the observed flux to the 0.1–100 keV band ($\sim 1.4 \times 10^{-7}$ ergs cm^{-2} s^{-1}). We assume $1.4 M_{\odot}$ for a neutron star and the $8 M_{\odot}$ average mass for stellar mass black holes reported by Özel et al. (2010).

- Our photometric campaign revealed an outburst amplitude $>$ 4.3 magnitudes, favouring an orbital period lower than $\sim$ 21 h and a companion star with a spectral type later than $\sim$ A0.
- The optical emission peaks at least 3 days after the hard X-rays. The observed optical and X-ray fluxes are consistent with J1745 being a black hole in the hard state lying at a distance of $1 \lesssim \frac{d}{1\,\mathrm{kpc}} \lesssim 7$.

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